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POLICY MODELING FOR ENERGY EFFICIENCY IMPROVEMENT IN US INDUSTRY*

Ernst Worrell, Lynn Price, and Michael Ruth
Energy Analysis Department, Lawrence Berkeley National Laboratory, Berkeley, California 94720; e-mail: EWorrell@lbl.gov, LKPrice@lbl.gov, MBRuth@lbl.gov

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■ **Abstract** We are just beginning to evaluate and model the contributions policies make toward improving energy efficiency. In this article, three recent studies are reviewed. They represent an important step in the analyses of climate-change mitigation strategies. All studies model estimated policy impacts rather than the policies themselves. Often the policy impacts are based on assumptions, as the effects of a policy are not certain. Most models incorporate only economic (or price) tools, which, for estimating impacts, costs, and benefits of mitigation strategies, recent studies have proven are insufficient. The studies reviewed are a first effort to capture the effects of nonprice policies. They contribute to a better understanding of the role of policies in improving energy efficiency and mitigating climate change. All policy scenarios result in substantial energy savings compared with the baseline scenario used; they also result in substantial net benefits to the US economy. Because the industrial sector is the most diverse and, arguably, the most challenging energy-demand sector to model, studying policies for them is no easy task. The challenges, which are many, fall into two categories: appropriate level of detail (i.e., sector, technology, and policy) and representations of decision making. A better understanding of decision-making behavior, technology choice, and policy impact and effectiveness is needed to improve our understanding of the potential effectiveness of future energy efficiency policies as well as to improve policy modeling. With these developments, the current and next-generation policy models and studies have the potential to become richer representations of the industrial sector.

CONTENTS

1. INTRODUCTION

Changes in energy intensity of industry are due to a movement toward less–energy-intensive industries and energy efficiency improvement. Energy-efficiency improvement is one of the key areas of the US national energy strategy (1). In the United States, the industrial sector is extremely diverse. It includes agriculture, mining, construction, energy-intensive industries, and non–energy-intensive manufacturing. In 1997, the industrial sector consumed 37% of the primary energy consumed in the United States. In this review, we focus on the manufacturing industry, which in the United States consumes the bulk of industrial energy use. Various bottom-up studies found cost-effective potentials for energy efficiency improvement varying from 5% to 12% by the year 2010 (2, 3), and up to 20% by the year 2020 (3), compared with business as usual, whereas other studies found less potential or higher costs to achieve the potentials (4).

Energy efficiency improvement can be achieved through the adoption of energy-efficient practices (e.g., energy management) and technologies. Many studies identified a wide variety of sector-specific and cross-cutting energy efficiency improvement opportunities (2). Sector-specific measures include technologies and practices that are unique to a specific process or industrial sector, e.g., scrap pre-heating in steel plants and new drying technologies in the paper and textile industries. Cross-cutting measures include technologies that are used more generally (although some applications may be sector specific) throughout industry, e.g., motor-and-steam system retrofits or cogeneration to replace aging boilers. Adoption of energy-efficient practices is influenced by issues such as stock-turnover rates, growth of production capacity, relative prices of production factors, regulations, and energy policies.

Energy policies are key to the implementing of practices and technologies identified in the studies mentioned above and will affect the degree of energy efficiency improvement that can be achieved in the United States. However, comprehensive evaluations of the effects and effectiveness of industrial energy policies are rare (5), as are studies that try to model energy efficiency policies. We are just beginning to evaluate and model the contributions policies make toward improving energy efficiency. In this article, we review recent studies in the United States that focus on modeling the impact of policy on energy use in manufacturing. Because of the emerging character of the policy-modeling field, this review, by definition, is a preliminary review. Despite the many interesting and important energy policy developments ongoing outside the United States, e.g., voluntary agreements in Europe, those are beyond the scope of this review.

Policy makers rely on scenario studies to evaluate, *ex ante*, the potential effects of certain developments and policy choices. This is frequently done using models that try to estimate the effect of the choices, e.g., on energy use and economic welfare. However, models, almost by definition, have shortcomings. One of the main shortcomings of current models is they cannot be used to properly assess the effect of policies on energy use. Hence, a critical evaluation of the value of the models and scenario results is needed.

We review past trends in industrial energy-use efficiency in the United States to provide a perspective on future trends. This is followed by a review of selected recent modeling studies aimed at assessing the potential for improving energy efficiency using policies. Many of the studies assessed the potential for improved energy efficiency to reduce greenhouse gas emissions. We review the methodologies used, as well as the results of those studies, and assess the dependence of policy on the possible potentials. We end with conclusions and recommendations with respect to modeling industrial energy efficiency policies.

2. TRENDS IN US INDUSTRIAL ENERGY USE AND POLICY EXPERIENCES

Although price shocks in the 1970s and early 1980s led to a temporary reduction, energy use in the United States has increased in the past decades (6). Today, because of strong economic growth, energy use has surpassed the historical high of the 1970s. A similar pattern is observed for CO_2 emissions (6). Only the manufacturing industry reduced total energy use and CO_2 emissions between 1970 and the early 1990s. This is mainly due to improved energy efficiency followed by a change, lasting until 1989, toward higher production value (7) (Figure 1); the contribution of the manufacturing industry to the Gross Domestic Product (GDP), however, has not declined. Most recently, trends suggest a change in the overall structure of the US economy, contributing to a decoupling of energy use and economic growth. Although energy prices and policies affect energy use, analyses are unable to directly measure their effect on energy use in manufacturing. Golove & Schipper (7) show that during and shortly after the price shocks of the 1970s and 1980s, the manufacturing industry reacted mainly by adapting the structure of the sector rather than by decreasing energy intensity (improving energy efficiency). Compared with such changes prior to 1970, the annual rate of change in energy-intensity has increased, but they were reduced in the second half of the 1980s, when energy

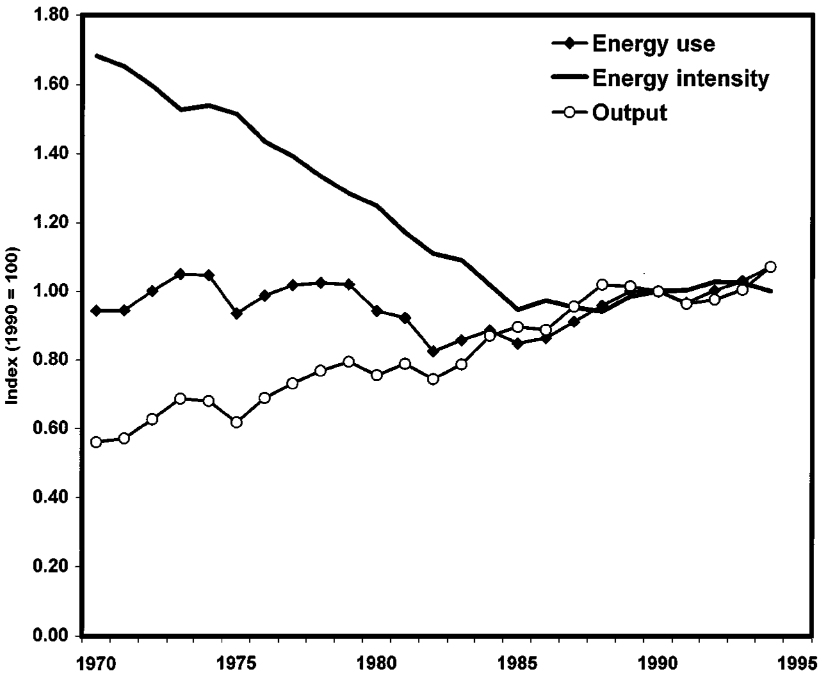

Figure 1 Development of value of output, primary energy use, and energy intensity of the US manufacturing industry. The information is indexed to the year 1990. (From Lawrence Berkeley Natl. Lab., Berkeley, CA.)

prices declined. A review of trends in 13 Organization for Economic Cooperation and Development (OECD) countries demonstrated that after energy prices declined in 1986, energy efficiency improvements took place (8). Although energy prices impact energy efficiency improvement, it is unclear how much.

The analyses discussed above used aggregate indicators to assess historic trends. Decomposition analysis helps to identify the role of energy efficiency and structural change. Still, these indicators may obscure the effects, as changes in commodity prices over time may not be fully captured in the analysis. Indicators using physical energy intensities (e.g., gigajoules/tonne of product) track the changes better at the level of individual industrial sectors, especially for energy-intensive sectors (9, 10), although these indicators too have disadvantages (10). Farla et al. (11) found that the US pulp and paper industry improved its energy efficiency by 15% in the period 1973–1991, equivalent to 0.9% per year on average. Worrell et al. (12) found that the average energy intensity reduction of the US iron and steel industry was equal to 1.5% per year. The average contribution of energy efficiency improvement was equal to 1.0% per year. These studies do not evaluate the relationship of found trends to the potential impact of energy policies or energy prices. Boyd & Karlson (13) studied the impact of energy price on technology choice in the steel industry. Their analysis shows that although energy prices play a role in energy efficiency improvement, energy prices are unlikely to influence adoption of innovative technologies. Other technology parameters, e.g., productivity, have a more important effect on this choice than does energy price.

Based on this limited review of recent trend analyses of energy use in the US manufacturing industry, it is difficult to evaluate the impact of energy policy on historic trends. Various studies have assessed the potential impact (*ex ante* or *ex post*) of individual policies. A 1996 US Department of Energy (DOE) report assessed part of the literature evaluating the effectiveness and feasibility of voluntary programs, research and development (R&D), regulations, and market-based incentives (14). Program-specific evaluations estimate the effect of a specific policy program, e.g., the audit program of the Industrial Assessment Centers run by the DOE (15) and the Energy Star program run by the US Environmental Protection Agency (EPA) (16). However, it is difficult to compare the effects of individual programs on trends in energy use and energy intensity in industry, and also to estimate the effectiveness of the programs. There is, however, a discernable effect of policies on industrial energy use and intensities. The lack of *ex post* evaluations makes it difficult to model the effects of industrial energy efficiency policies.

3. POLICY MODELING STUDIES

In this section, we review several recent modeling studies that assessed the potential impact of energy policies on future energy use, as well as on greenhouse gas emissions. We review recent studies that explicitly modeled (industrial) energy policies (17–19).

The studies modeled policies in different ways. Basically, they all translated the policies into effects on technology and the energy efficiency of the technologies, either exogenously or within an integrating model. Table 1 provides an overview of the modeling approaches used in the various studies [for an in-depth description of the models used, see elsewhere (20, 21)]. The studies use either the 1998 (Tellus) or 1999 [American Council for an Energy-Efficient Economy (ACEEE), Clean Energy Future (CEF)] Annual Energy Outlook (AEO) baseline scenarios, as produced annually by the Energy Information Administration (EIA). This allows a comparison of the results between the various studies. The baseline scenarios used in these studies assume a future governed by relatively low energy prices (i.e., small increases in fossil fuels and reductions in electricity due to deregulation) and strong economic growth.

The study by Geller et al. (17) is an exploration of 10 major energy policies in different sectors that either have proven to be effective policies (e.g., efficiency standards for household appliances) or are, according to the authors, likely to have a large impact (e.g., public benefit charges, industrial cogeneration). The

TABLE 1 Modeling approaches of the studies reviewed[a]

Model characteristics	ACEEE 1999	Tellus 1999	CEF 2000
Model	Spreadsheet	NEMS/LIEF	NEMS
Baseline scenario	AEO 1999	AEO 1998	AEO 1999
Industrial subsectors	1	18	15
Individual technology representation	No	No	No
Policy modeling	Off line	Off line	Partially off line
Cost calculation	Net present value	Net present value	Annualized
Macroeconomic impacts included	No	Yes	Yes

[a]Note: off line denotes that the actual modeling of policies is executed outside the integrating model used to estimate the scenario results. ACEEE, American Council for an Energy-Efficient Economy; CEF, Clean Energy Future; NEMS, National Energy Modeling System; LIEF, long-term industrial energy forecasting; AEO, Annual Energy Outlook.

set includes two policies specific for the industrial sector, i.e., cogeneration and voluntary sector agreements. Using simple spreadsheet tools, the authors explore the potential effect and costs of each of the five policies and offset the results to the AEO 1998 baseline scenario. The study assesses results for the years 2010 and 2020. The study results achieve the emission reductions necessary under the Kyoto Protocol, if the United States ratifies the Kyoto Protocol.

Bernow et al. (18) looks at the potential policies and the effects on US carbon dioxide emissions in light of the Kyoto Protocol. Hence, it assesses only the potential effects until 2010. The study was done as part of the World Wildlife Fund's Climate Change Campaign and identifies strong emission-reduction potentials in all sectors. It studies two scenarios: Kyoto compliance (KC) and climate protection (CP) (climate protection assumes even further reductions than are needed to comply with the targets set out in the Kyoto Protocol, without the flexible mechanisms defined in the Kyoto Protocol). It uses various models to study the policy impacts, employing the National Energy Modeling System (NEMS) as the integrating framework.

The CEF study (19) is the most comprehensive of the studies reviewed. It is a collaborative study of five national laboratories, aiming at modeling various policy scenarios to explore different energy futures. It is an independent, follow-up study to the so-called Five-Lab study (2, 22). In the Five-Lab study, only technical and economic opportunities for efficient use of energy were studied, whereas the CEF study explores the effects of policies as well. The study assesses a business-as-usual scenario (slightly different from the AEO 1999 scenario) and two policy scenarios: a moderate and an advanced scenario, each reflecting increasing levels of public commitment to solving the energy-related challenges in the United States; these advanced scenarios enable policies to be implemented that may not be feasible today. The CEF study is different from the other two studies in that it is not primarily driven by the potential threat of climate change; instead, it tries to address different energy-related problems, of which climate change is a major one. The study assesses the impacts of the scenarios both for 2010 and 2020 and mainly used NEMS as the modeling tool, although exogenous models were used to model some of the policy impacts.

3.1. Modeling Approaches

In this section, we focus on the so-called engineering-economic (or "bottom-up") models, as they include the amount of detail commonly needed to model policy scenarios. Although macroeconomic models have been used to evaluate the effect of economic or price policies, these models are not sufficiently detailed to accurately assess the effects of policies. For an excellent discussion of the limitations of macroeconomic models, see Laitner et al. (23). Laitner et al. (23) critique macro-economic models on four levels: (*a*) the lack of realism (e.g., the assumption of ideal behavior with perfect information, the lack of technology dynamics); (*b*) the assumption that the current state is "efficient"; (*c*) the use of similar behavior at aggregated levels of the society; and (*d*) the narrow concept of welfare used in these studies. The engineering-economic approach is rooted in engineering principles to account for physical flows of energy and the use of capital equipment. This is coupled with economic information to account for energy expenses and investment in capital. Some decision-making rules are applied. The form of the decision-making rules presents a challenge to modeling industrial energy use because for industry, in times of relatively low energy prices, energy issues alone rarely drive investment decisions. Other challenges in engineering-economic modeling include representing the activities in "industry," which are diverse, as well as the lack of data and hence calibration of the results. Various models have been used in the United States to model energy use. Three often used are NEMS, LIEF (long-term industrial energy forecasting), and ISTUM (also known as ITEMS).

3.1.1. INDUSTRIAL-SECTOR TECHNOLOGY USE MODEL ISTUM was originally developed by the DOE in the 1980s. It is used in Canada and the United States under the names ISTUM and ITEMS. The ISTUM model includes the most detailed technology breakdown of the models considered here. However, ISTUM is not used in any of the studies discussed below, so we do not discuss this model in detail. Roop & Dahowski (24) used it to assess the AEO 2000 baseline scenario as developed by the EIA (using NEMS) and found that a technology-rich model like ISTUM would produce a baseline scenario with lower energy use and emissions than a less-rich model like NEMS.

3.1.2. NATIONAL ENERGY MODELING SYSTEM Although NEMS is not specifically used to obtain any of the policy/scenario results for the studies, it underlies the results of the CEF (19), Interlab (2), and Tellus (18) studies because their base cases, taken from the EIA, were calculated through NEMS. Because NEMS is used for EIA's energy forecasting, understanding its approach is important to discussions of industrial-sector energy modeling. In NEMS, energy use is modeled at the energy-service demand or process-stage level, although for some sectors no equipment is explicitly modeled. A technology is represented by a parameterized value, i.e., unit energy consumption (UEC), which is the energy use per unit of production. For nonmanufacturing and non–energy-intensive manufacturing, each fuel-specific UEC applies to the entire production process for which the output is defined in monetary terms. For the energy-intensive sectors, UECs are given at different process levels. UECs are specified for both new and retrofitted equipment, and the UECs change over time according to a technology possibility curve (TPC). This gives the ultimate UEC that a process will reach at the end of the analysis period. The actual UEC moves along the TPC with each year of the analysis. The user can also specify the turnover rate for equipment to model the penetration of more efficient technologies.

The NEMS industrial module contains no explicit equipment characterizations, but the UEC and TPC parameters can be calculated based on assumptions of technology performance and penetration. These estimates are an exogenous input to the model, so there is no way to model technology choice or to capture feedback from the scenario, such as price changes on technology choice. For the baseline scenarios of the Tellus and CEF studies, the Arthur D. Little Corp. developed the inputs (21). For the CEF policy scenarios, new NEMS inputs were developed.

3.1.3. LONG-TERM INDUSTRIAL ENERGY FORECASTING The heart of the LIEF model (20) is a set of conservation supply curves. There are curves for 18 separate industries that show the relationship between cost-effective savings and energy prices for each industry. These 18 groupings represent industries with similar energy use and growth characteristics. Each industry has two curves, one for electricity and one for aggregate nonelectric fuels. These curves are parameterized by two variables: G_0, the efficiency gap, or the percentage of energy use that could be reduced cost-effectively in the base year; and A, an elasticity parameter showing how industry energy use changes in response to changes in energy prices. The values of these parameters are estimated from historical observations. Assumptions about a base year and historical capital recovery factor are needed for estimating these parameters; these values were chosen based on a "behavioral" discount rate of 33% (20). A third industry-specific variable is an autonomous-trend variable. This parameter has also been estimated from historical observations to explain changes in energy intensity that are not explained by changes in energy prices. This autonomous trend encompasses energy efficiency changes that accompany other productivity enhancements, changes in structure, and process changes. The trend may actually be an increase in energy intensity in some industries; for example, where an industry is becoming electrified, the electricity energy intensity may increase.

The relationship is expressed as potential energy savings with respect to energy price divided by the capital recovery factor (CRF). The CRF folds several factors into the analysis, including time preference for money, risk aversion, and investor strategy; it may be seen as a “hurdle” rate. The CRF therefore provides a basis for modeling policy interventions ranging from financial mechanisms, such as subsidies and tax incentives, to informational programs and other nonfinancial policy changes. Although the option to model these policies exists, there is a need for offline empirical analyses to translate policy changes into estimates of hurdle rate changes. To this end, it is desirable, when feasible, to break the hurdle rates down into the various factors that comprise it so they can be understood and treated separately in policy modeling.

In LIEF, the other variable that can be used for policy modeling is the penetration rate. LIEF calculates an “ideal energy intensity” given the expected energy prices and discount rates and then uses a penetration rate to reflect the extent to which an industry moves from the actual energy intensity toward the ideal energy intensity each year. Policies are modeled in LIEF by changing the values of the CRF and/or the penetration rate to reflect certain policies. The year-by-year difference in energy consumption between this LIEF run and the LIEF version of the base case is then subtracted from the EIA base case to obtain the policy case.

3.2. Baseline Scenarios

Most studies use the AEO 1998 (25) or 1999 (26), developed by EIA as baseline. The AEO 1998 scenario is used by the Tellus study (18), while AEO 1999 is used by the ACEEE study (17). On the basis of the AEO 1999 scenario, the CEF study has developed a different baseline scenario using assumptions about stock turnover rates and adjustment in base year (1994) energy intensity different from those for selected sectors (19). The CEF baseline scenario results in a slightly lower industrial primary energy consumption [43 EJ (10^{18} J)] by the year 2020 than does the AEO 1999 scenario (44.5 EJ). A recent analysis of the AEO 2000 has shown that a “technology-rich” modeling approach may lead to different results for the baseline scenario and may result in a lower estimate of future energy use in industry (24, 28). This stresses the importance of the applied modeling approach, both for the baseline scenario as well as for policy scenarios (see above).

3.3. Policy Scenarios

The extent to which individual policies are covered in an analysis varies widely. Table 2 provides a summary of the groups of policy measures included in the studies. As Table 2 shows, the study by the Interlaboratory Working Group (19) is the most comprehensive of the three.

We distinguish various categories of programs. Voluntary sector agreements are applied only in the CEF study, modeled after European programs (29, 30). Voluntary sector agreements between government and industry are applied as the key policy mechanism in the CEF study to attain energy efficiency improvements and to reduce greenhouse gas emmissions because an integrated policy that accounts for the diverse characteristics of technologies, plant-specific conditions,

TABLE 2 Policy instruments included in the studies reviewed[a]

Category/instruments	ACEEE 1999	EIA 1999	Tellus 1999	CEF 2000
Voluntary sector agreements	+			+
Voluntary programs				+
Information programs				+
Investment enabling programs	+[b]		+[c]	+[c]
Regulations				+
Research and development	+[b]		+	+
Emission trading program	+[d]		+[d]	+
Cogeneration—investment enabling	+	+	+	+
Cogeneration—barrier removal	+		+	+

[a]The study by the Energy Information Administration (EIA) is added for completeness but is not evaluated in this review because of the limited scope of the study. ACEEE, American Council for an Energy-Efficient Economy; CEF, Clean Energy Future.

[b]As part of public benefit programs of utilities but not specifically targeted to manufacturing industry.

[c]Tax incentives.

[d]For power production only. This will likely affect electricity costs for industry.

and industrial-sector business practices is needed. Policies and measures supporting these voluntary sector agreements take into account the diversity of the industrial sector while (*a*) being flexible and comprehensive, (*b*) offering a mix of policy instruments, (*c*) giving the right incentives to the decision maker at the firm level, and (*d*) providing the flexibility needed to implement industrial energy efficiency measures. Voluntary agreements are also used in the study by ACEEE (17), although the modeled impact is based on preliminary results of the CEF study.

For industrial energy policy in the United States, voluntary programs have been widely used, in the Challenge technology delivery programs, Energy Star Buildings and Green Lights, Climate Wise, and specific pollution prevention programs. Voluntary programs are included explicitly only in the CEF study, although other studies may have included it partially in the baseline scenario. The DOE's Motor Challenge program was created in 1993 to promote voluntary industry/government partnerships to improve energy efficiency, economic competitiveness, and the environment. The main goal of the program is to work in partnership with industry to increase use of energy-efficient, industrial, electric-motor–driven systems. A key element in the Motor Challenge strategy is to encourage a "systems approach" to industry's selection, engineering, and maintenance of motors, drives, pumps, fans, and other motor-driven equipment (31). The current Motor Challenge program focuses on eight energy- and waste-intensive sectors: forest products, steel, aluminum, metal casting, chemicals, glass, mining, and agriculture. It is also targeting large plants in these industries (31). Similar

Challenge programs are aimed at steam systems (Steam Challenge), compressed-air systems (Compressed Air Challenge), and Cogeneration [combined heat and power production (CHP Challenge)]. The EPA's Energy Star programs help to eliminate information barriers and improve efficiency in investments in the buildings component (especially important in light industries) of industrial energy use. Energy Star programs are voluntary partnerships between the EPA, the DOE, product manufacturers, local utilities, and retailers to develop and market energy-efficient products (see above). Partners help promote energy-efficient products by labeling with the Energy Star logo, which may be used as a marketing tool, and by educating consumers about the benefits of energy efficiency. Participating companies are provided with access to information about products and practices to improve their efficiency. The Green Lights program, a voluntary pollution prevention program sponsored by the EPA and part of the Energy Star program, aims at improving the efficiency of lighting systems. Green Lights partners agree to install energy-efficient lighting where profitable as long as lighting quality is maintained or improved. Many industries are a partner in this program.

Information programs include audit, labeling, and dissemination programs. The United States has wide experience with a program that audits small and medium-sized enterprises, based on a network of 30 universities through the DOE Office of Industrial Technology's Industrial Assessment Center (IAC) program. Since its inception in 1976, these centers have performed more than 8000 assessments and provided 53,000 recommendations; about 42% of the suggested investments have been implemented (15). Because of the higher percentage of small and medium-sized enterprises, most current clients of the IAC centers are in food processing and metals manufacturing. Historically, IAC assessments have identified lighting, heating, ventilation, and air conditioning (HVAC) and building envelopes, heat recovery and containment, compressors, and motors as the areas where greatest improvement in energy efficiency is possible.

Investment-enabling programs include financial incentives, such as investment tax rebates and subsidies for investment in energy-efficient technologies, as well as state and energy service company/utility programs. Currently, many states and regional bodies have local industrial innovation and competitiveness programs; a number of these programs aim specifically at industrial energy efficiency improvement. Approximately 300 regional or state programs exist. Examples of successful energy programs can be found in Iowa, New York, and Wisconsin. The Energy Center of Wisconsin focuses on demonstration projects. A program in New York focuses more on industrial R&D, whereas the LoanSTAR program in Texas focuses on demonstrating energy retrofit technologies. The Iowa Energy Center focuses on agriculture and audits. Following deregulation, 19 states have introduced public benefit charges. The revenue from the public benefit charges will be used to fund projects in energy efficiency, R&D, and renewable energy sources to subsidize low-income households. The charge and the spending patterns vary by state (32, 33). Historically, utility demand-side management program performance has varied widely and depends on factors such as marketing, targeting of approaches, program procedures, level of financial incentives, and availability of technical assistance (34). Utility programs seem to have been targeted mainly to larger customers. Public benefit charges are explicitly modeled in the ACEEE and CEF study, although the assumed use of the funds may vary.

Regulations exist in the United States for industrial motors, as well as for as for large heating and cooling equipment. Motors use 59% of manufacturing electricity use, or 541 TW hours (TWh) (35). The Energy Policy Act (EPACT) standards apply to all industrial motors with a power rating of 1–150 kW. Potential new standards include improved rewind practices by promoting a national repair standard. The CEF and ACEEE studies include new motor standards, as well as extension to other motor sizes. The other studies include standards for other equipment (e.g., lighting, office equipment, and domestic appliances) but do not explicitly include motor standards.

Many new technologies are being developed that could have a large impact on industrial energy efficiency. Expanded R&D efforts are likely to generate future energy savings over the modeled time frame depending on timing and scheduling of the R&D (36). The Tellus study and CEF study explicitly include R&D policies for industrial energy efficiency in the policy scenarios. Current R&D programs in the United States include federal activities (mainly managed through the DOE) and state programs. Federal programs include such demonstration programs as National Industrial Competitiveness through Energy, Environment, and Economics. Grants support innovative technology deployment that can significantly conserve energy and energy-intensive feedstocks, reduce industrial wastes, prevent pollution, and improve cost competitiveness. The DOE Office of Industrial Technologies, Industries of the Future strategy—creating partnerships among industry, government, and supporting laboratories and institutions to stimulate technology research, development, and deployment—is being implemented in nine energy-intensive industries.

A cap and emission trading program for CO_2 emissions is found in only the CEF study and in only one policy scenario. The cap and trade system is modeled through a shadow price for CO_2 emissions in the CEF study and works along the same principle as sulfur emission trading for power generators.

Industrial cogeneration (CHP) is an important option included in all studies, although in different ways. The analysis of the Climate Change Technology Initiative (37) includes only the tax rebate given to eligible CHP projects until the year 2003. The other studies assess a more aggressive package of policies aimed at reducing the barriers that limit the profitability and uptake of CHP in industry. The extent of the instruments varies within each of the studies. CHP is the only policy explicitly modeled in all studies, although mostly offline, using estimates for the potential penetration. In addition to including effects of many policy initiatives (e.g., removal of such barriers such as high interconnection and backup charges, exit fees, or low buy-back tariffs), CHP policies also include replacement of retired industrial boilers, voluntary programs, air-pollution–abatement programs, public benefit programs, investment tax credits for CHP systems, and expanded R&D programs.

4. COMPARING THE RESULTS OF THE STUDIES

Given the large differences in inclusion of various policies and programs, comparison of the results should be done carefully. We first compare the overall results to put the findings for industrial energy use in perspective. We then compare the results for industrial energy use and the impacts for specific areas or policies that have been modeled explicitly in the studies, i.e., cogeneration.

4.1. Total Primary Energy Use and Carbon Emissions

In all studies, total US primary energy use is expected to increase over 1990 levels by the year 2010. However, total energy use varies considerably by study. Although primary energy use by 2010 in the reference case (AEO 1ggg) is estimated at 117 EJ (EJ $= 10^{18}$ J), the CEF study shows the most moderate results. Even in the CEF advanced scenario, discussed above, primary energy use is higher (105 EJ) than in the policy scenarios of the other studies, which aim at achieving the Kyoto targets for CO_2 emission reduction. According to the ACEEE study (17), by 2020, the gap widens even more because of the large impact of cogeneration in particular. The Tellus policy scenarios (18) do not evaluate the impact for the year 2020. Figure 2 depicts the scenario results for total primary energy use in the United States for the different studies, as well as the baseline assumptions used in the studies.

CO_2 emissions decline in all policy scenarios compared with the baseline scenario, whereas the differences between the studies become even wider, as shown in Figure 3. In the reference scenario, AEO 1ggg, CO_2 emissions are estimated to increase to almost 1800 million tons of C (MtC) by 2010 and to 1900–2000 MtC by 2020, compared with 1990 emissions of 1346 MtC. The CEF study (19) finds that total 2010 carbon emissions are estimated to be 1684 MtC and 1467 MtC for the moderate and advanced scenarios, respectively. The Tellus Kyoto compliance scenario (18) and the ACEEE policy scenario (17) achieve the emission target for the United States set under the Kyoto Protocol, whereas the Tellus climate protection scenario (18) finds further opportunities for emission reduction beyond the Kyoto target. The differences between the energy and emission results suggest that the larger variation in emission results are due to more rapid changes in fuel mix. The results of the ACEEE study (17) show a further reduction in emissions by 2020, especially through the sharply increased reliance on cogeneration in this study compared with the CEF study (19) and baseline scenarios, as well as through other more aggressive policies in other sectors. (It is outside the scope of this review to compare the results for the total US economy in depth.)

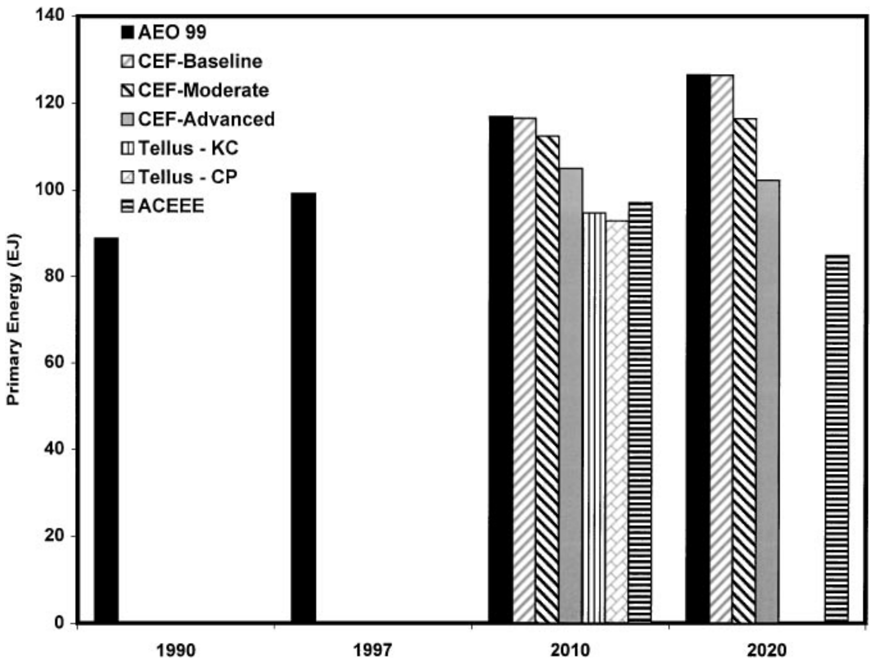

Figure 2 Primary energy use (in exajoules) in the United States as estimated in the scenario studies, as well as baseline energy use (1990, 1997, 2010, and 2020). AEO, Annual Energy Outlook; CEF, Clean Energy Future; KC, Kyoto compliance; CP, climate protection; ACEEE, American Council for an Energy-Efficient Economy.

4.2. Industrial Primary Energy Use and Carbon Emissions

Recent trends in US industrial energy use show a slow growth, from 33.9 EJ in 1990 to 36.6 EJ in 1997 (about 1% per year). Under the AEO 1999 scenario (26), industrial energy use is expected to grow to 41.6 EJ by 2010 (+1.0% per year) and to 44.4 EJ by 2020 (+0.8% per year). The CEF study (18) uses a slightly lower energy consumption in the reference scenario, AEO 1ggg (40.7 EJ and 43.3 EJ in 2010 and 2020, respectively). Figure 4 depicts the results for the different studies.

The CEF moderate scenario (19) of primary energy consumption by industry is estimated at 39.2 EJ by 2010 (−4% compared with the baseline) and 40.1 EJ by 2020 (−7% compared with baseline scenario). In the advanced scenario, industrial energy efficiency further improves, leading to primary energy consumption of 36.6 EJ by 2010 (−10%) and 36.2 EJ by 2020 (−16%). The other studies assume more aggressive policies, leading to higher reductions in energy consumption. The results of the other three scenarios are more or less similar, varying between 34.5 and 34.8 EJ by 2010. This is comparable to a reduction of 16%–17% compared with the baseline scenario (26). The ACEEE study (17)

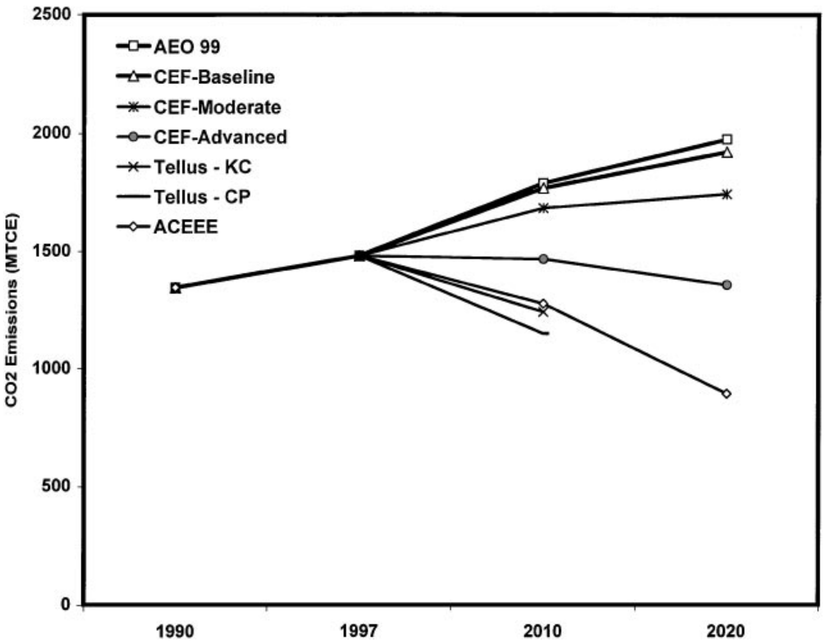

Figure 3 Total CO_2 emissions (in million metric tons of carbon equivalent) in the United States as estimated in the scenario studies. (For abbreviations, see Figure 2.)

expands the time horizon to 2020, showing a further reduction in primary energy use to 32.9 EJ (−26%). This strong reduction is due in particular to a dramatic increase in industrial cogeneration, as well as voluntary industrial-sector agreements.

Use of aggregate energy intensities is a reasonable way to compare policy effects with historic trends, as well as a way to compare the results. The drawbacks of using an aggregate indicator are limited in this comparison because all scenario studies use similar forecasts for the economic structure of the industrial sector. Unfortunately, only the CEF study presents the average reductions in energy intensities. In the baseline scenario (19), energy intensity is forecast to decrease from the 1997 level of \$9.2/GJ to \$7.1/GJ [on a primary energy basis, excluding the effects of industrial cogeneration (see below)], equivalent to an average reduction of 1.1% per year [of which 70% is due to structural change within the industrial sector (26)]. Under the CEF moderate scenario, aggregate energy intensity is expected to decrease by 1.5% per year and in the advanced scenario by 1.8% per year (19). Although high, such changes are still smaller than historic rates of change, as found during the oil price shocks.

Carbon dioxide emissions are being reduced faster than primary energy use because of changes in fuel mix in industry and in power generation in all scenarios. The effects of the different policies vary, which is mainly due to penetration of

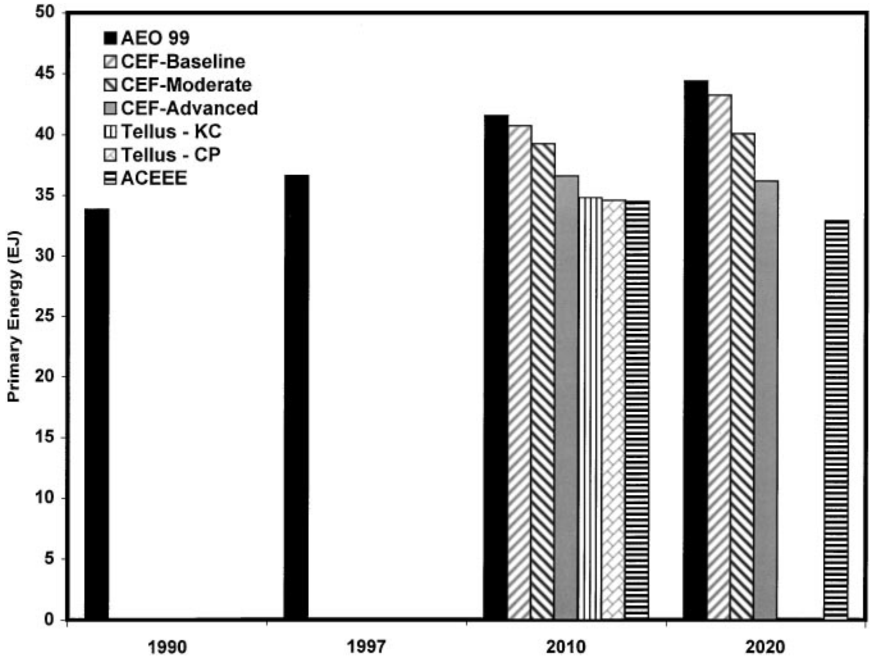

Figure 4 Primary energy use (in exajoules) in US industry as estimated in the scenario studies, as well as baseline energy use (1990, 1997, 2010, and 2020). (For abbreviations, see Figure 2.)

low-green house gas (GHG) power generation technologies (including cogeneration). Figure 5 depicts the results of the different scenarios and studies.

There is an estimated 9% reduction in CO_2 emissions by 2010 in the CEF moderate scenario (19) and a 22% reduction in the advanced scenario (19). The estimates are even larger in the ACEEE (28%) (17) and Tellus (33% respectively 38%) studies (18). The differences between the CEF and ACEEE scenarios are growing by 2020. The CEF advanced scenario finds CO_2 emissions of 399 MtC by 2020 (−31%), whereas the ACEEE policy scenario finds emissions of 298 MtC (−48%). The large reduction in the ACEEE scenario is due in particular to cogeneration, as well as to changes in power production.

4.3. Industrial Cogeneration

Because the studies differed in the way that industrial cogeneration was integrated in the total results of the industrial sector, and because of the importance of this measure in all studies, we compare the results for industrial cogeneration separately. We assess the total installed capacity as well as generated power by cogeneration.

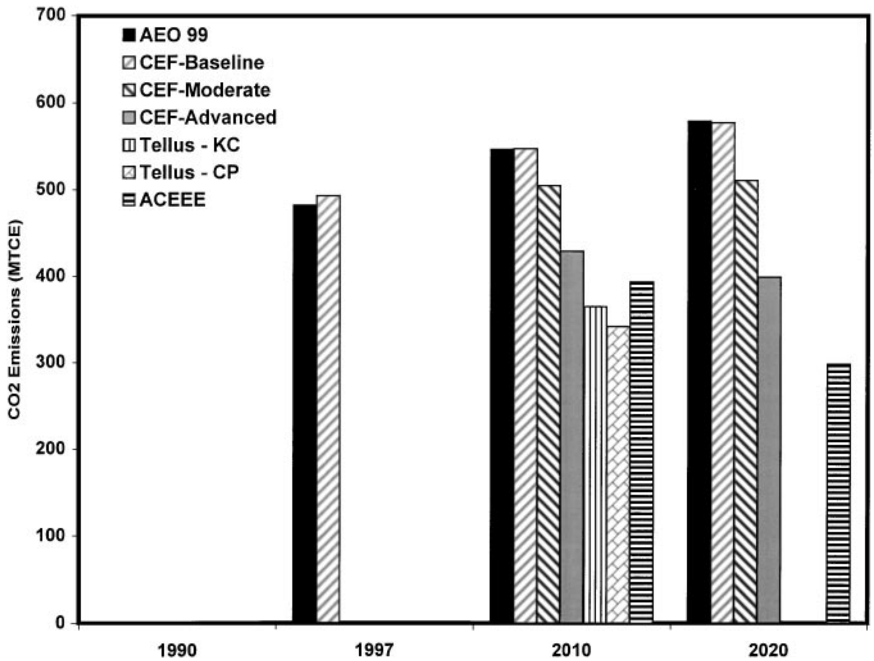

Figure 5 Total CO_2 emissions (in million metric tons of carbon equivalent) from the US industry as estimated in the scenario studies. (For abbreviations, see Figure 2.)

Currently, cogeneration contributes less than 9% to the total amount of power generated in the United States. This is a limited quantity compared with other industrialized countries, which suggests the existence of additional potential for (industrial) cogeneration. Compared with district heating applications, industrial cogeneration applications are more likely over the short term because of higher profitability (e.g., larger size, lower capital cost) and constant heat consumption demand.

Total power generation in the United States is forecast to grow from 745 GW in 1997 to 854 and 974 GW in 2010 and 2020, respectively. In the baseline scenario (26), installed industrial cogeneration capacity increases slowly, at 0.8% per year, leading to just over 50 GW installed by 2020. All policy scenarios assume a much larger role of cogeneration in future power supply, by reducing barriers (e.g., interconnection charges, transition or exit fees in various states, environmental permitting, and tax depreciation schedule) as well as tax incentives (as currently available under the Climate Change Technology Initiative). This leads to construction of additional cogeneration capacity of 10 GW over the baseline forecast (CEF moderate) to highs of 38–49 GW (Tellus and ACEEE, respectively). The CEF advanced scenario (19) forecasts an additional capacity of 25 GW (see Figure 6). The official goal of the US government is to double existing cogeneration capacity by

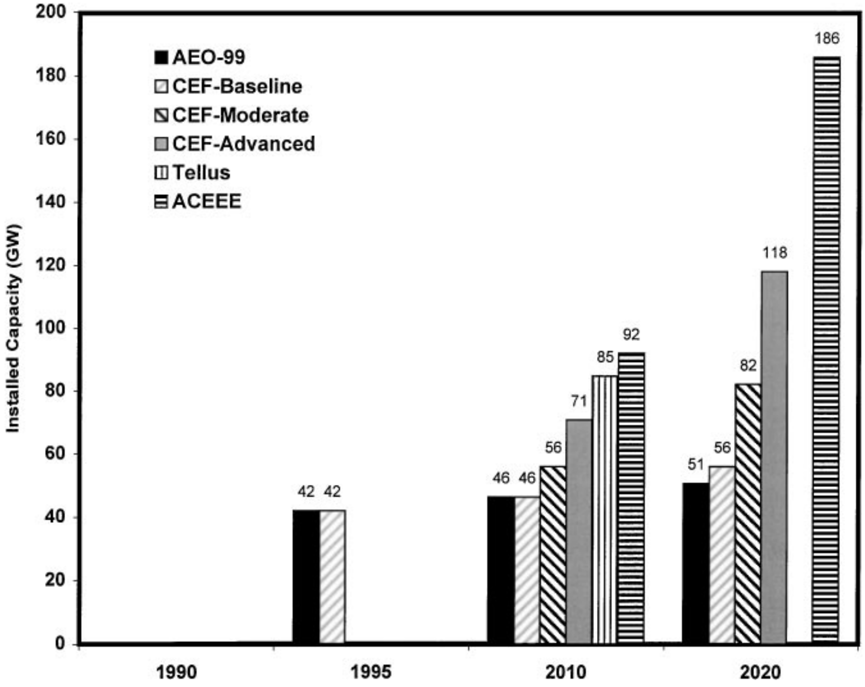

Figure 6 Installed industrial capacity of combined heat and power (cogeneration) in the scenario studies (expressed in gigawatts). (For abbreviations, see Figure 2.)

2010 [i.e., construction of cogeneration capacity to create an additional capacity of about 46 GW (not all industrial)]. The Tellus (18) and ACEEE (17) studies assume this new capacity will be all industrial capacity, whereas the CEF study assumes implementation of only part of the "challenge" in the industrial sector. By 2020, the differences between the two studies are even larger. The CEF moderate and advanced scenarios forecast 82 GW (+26 GW over baseline forecast) and 118 GW (+62 GW) total installed capacity by 2020, whereas the ACEEE study assumes 186 GW (+135 GW) (17).

The slow growth of cogeneration in the AEO 1999 scenario (26) leads to an actual reduction in the share of cogeneration in total US power supply by the year 2020. The total share of industrial cogeneration is estimated at 6% in 1997, and under the AEO 1999 scenario, this is forecast to be reduced to 5% of installed capacity. In the policy scenarios, the share is estimated to increase to between 7% and 11% by 2010. It is estimated to remain stable by 2020 (CEF moderate) or to increase to 8% (CEF advanced) or even 19% (ACEEE policy). Similar contributions have been achieved in some Western European countries (e.g., The Netherlands, Germany).

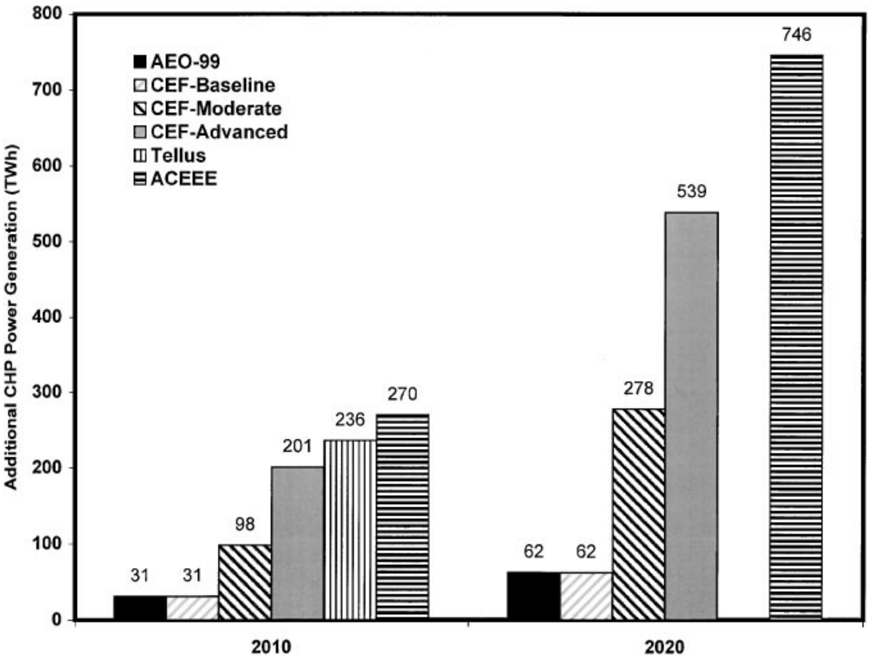

Figure 7 Power production from industrial combined heat and power production in the scenario studies (expressed in Terawatt hours). (For abbreviations, see Figure 2.)

The amount of generated power depends on the installed capacity and assumed production patterns (operation time). Figure 7 depicts the total amount of generated power in industrial cogeneration for each of the reference and policy scenarios for 2010 and 2020. Figure 7 shows that the ACEEE study (17) expects the largest power production to come from industrial cogeneration by 2010 and 2020, whereas the CEF study (19) is less optimistic. Still, all policy scenarios show a large increase in additional industrial power generation, tripling (CEF moderate, 98 TWh) the baseline forecast (AEO 1999, 31 TWh), or even exceeding it by a magnitude of one (ACEEE policy, 270 GW). By 2020 the role of industrial cogeneration is growing considerably in all scenarios, including the CEF moderate scenario (278 TWh), the CEF advanced scenario (539 TWh) (19), and the ACEEE policy scenario (746 TWh) (17).

Most industrial cogeneration in the studies is based on gas turbine systems. The CEF study (19) also assumes increased application of emerging technologies, such as black liquor gasification, leading to increased use of biomass. Hence, cogeneration not only results in improved efficiency but also in fuel-mix changes, away from a coal-dominated power sector in the United States. This will result in additional CO_2 emission reduction.

4.4. Policies

As Table 2 shows, only a few policy instruments are applied in all three studies, e.g., tax incentives [not specifically for industry in two studies (ACEEE/Tellus)], R&D [not specifically for industry (ACEEE/Tellus)], cogeneration tax incentives, and cogeneration barrier removal. Emission trading programs are used in all studies, but not specifically for industry, whereas voluntary sector agreements are applied only in the CEF (19) and ACEEE studies (17). Even when similar policies are used, they have been modeled in different ways, as shown by the discussion of industrial cogeneration (see Section 4.3).

The results of the voluntary sector agreements can not be compared, as the results of the ACEEE policy scenario (17) are derived from the CEF advanced scenario (19). Tax incentives and R&D are modeled as part of public benefit programs (within the power sector deregulation in the United States) in the ACEEE study and modeled as general measures in the Tellus study, although both studies estimate the effects of those measures on industrial CO_2 emissions. Unfortunately, the studies do not report on the effects on energy use, whereas the CEF study does not report on the emission reductions for each modeled policy (just energy use).

Regrettably, comparison of direct policy impacts in the different studies, other than cogeneration, is not possible, given the constraints in presentation of the study results.

4.5. Costs and Benefits

One of the benefits of the engineering-economic modeling approach is that the use of economic cost data for decision making allows for calculations to associate costs with energy savings and carbon reductions. Unfortunately, the approaches used by the three studies reviewed here differ in many ways that hinder comparisons. Two major difficulties in doing cost calculations lead to the differences in the studies.

The first difficulty is that capital investments in energy-efficient equipment are "instantaneous," whereas the energy savings they generate are not. In other words, the energy and carbon savings reported for 2010 cannot be attributed to investment in 2010 alone but to investments from every preceding year the equipment has been in use. Similarly, the investments for 2010 do not lead to savings only in 2010 but to all the years the equipment lasts. To address this problem, some method of "annualizing" or "levelizing" costs must be undertaken, which spreads the capital costs over the lifetime of the equipment. The CEF study (19) gives annualized results, whereas the other studies present net present values over the modeled period. However, this makes a comparison difficult, as two pieces of information are needed to do this comparison: the lifetime of the equipment and the discount rate to account for the time value of money used in the studies. Neither of these values is simplistically defined.

The second difficulty arises from the interaction of the electricity supply and demand sectors. Since power sector policies can reduce emissions in the demand sectors and demand sector policies can lower demand (and hence costs) for the utilities, sorting out the costs and emissions reductions can be complicated. All the studies try, to some extent, to integrate changes in the electric sector into their scenarios, so there is an issue of how to account for reductions in indirect emissions, i.e., those arising from electricity use. In general, utility policies to lower the carbon content of electricity have positive costs, while lowered demand for electricity requires fewer plants to be built, thereby lowering costs. Measurements of the costs of conserved energy should take into account avoided costs arising both from lower energy purchases and from avoided capital expansions to generate that energy in the power sector.

All studies present the total costs and benefits of the policy mix to achieve emission reduction, based on the investments needed, although only one specifies the program costs (CEF), whereas two contain assessments of the macroeconomic impacts of the policy scenarios (CEF, Tellus). Only the CEF (19) and Tellus studies (18) provide costs for the industrial sector separately. A direct comparison of the costs is not possible, as the studies use different costing methodologies. However, all policy scenarios in the studies show net benefits to the US economy, including investment and program costs (CEF only), even though the studies exclude environmental externalities. For the year 2020, results may be different because of the effects of earlier investments in R&D. In the CEF advanced scenario (19), industry shows net costs for industry by 2010, which are expected to result in net savings by 2020, when R&D investments start to pay off. The results are in line with other assessments that allow technology development, as these models do (e.g., see 28).

5. DISCUSSION

Although all studies use similar starting points (e.g., baseline scenario, energy prices, economic structure), it was difficult to compare the results directly because of differences in applied methods, system boundaries, sector, technology, and policy representation. Generally, all studies modeled policy impacts rather than the policies themselves. This is due to the complex interaction of decision-making behavior of stakeholders, policy, and business environment. Representations of decision making in the industrial-sector models are, with few exceptions, not very satisfying. Although the decision-making process is not fully understood, some models surveyed here capture at least the essence of choice as applied to technology. There is a need to identify key variables and relationships that affect the process, and analysts who developed both the LIEF and ISTUM/ITEMS models have used this information on technology decision making to derive these parameters. Of the studies discussed in this paper, only LIEF includes parameters that can be altered to reflect behavioral variables. Although the links are indirect, calibration of the parameters is based on historical data (LIEF). Hence, the modeling of policy impact and policy is and remains an important challenge.

A recent international conference discussed the challenges in modeling of the economic and policy potential for energy efficiency improvement. It concluded that the development of a more complete analysis of the achievable potential for energy efficiency improvement, including policy modeling, is needed, especially for noneconomic and nonregulatory policies. The workshop was not able to conclude on the need for more complex models to simulate decision-making behavior or use more simple and transparent models (38). The studies reviewed in this article tried to assess the achievable potential given selected policy instruments. Although all studies use off-line assessments to assess the policy impact of most policies, some selected policies have been modeled using models to simulate decision-making behavior in relatively simple economic terms (e.g., LIEF, NEMS).

Even though all studies use a similar definition of the industrial sectors, we found that the CEF study was not able to fully integrate industrial cogeneration in the results for the industrial sector because of limitations with the integrating model that was used (Lawrence Berkeley National Laboratory—NEMS). The other policy studies build heavily on cogeneration to reduce industrial primary energy use, which makes it difficult to compare the overall results. We did evaluate the results for cogeneration impacts. The potential effects of policies aimed at reducing barriers to market penetration of cogeneration vary widely between the different studies, whereas the ACEEE study (17) particular finds a large potential for industrial cogeneration by the year 2020, generating about 750 TWh annually, compared with 540 TWh for the CEF advanced scenario. On the other hand, although the CEF study (19) uses a detailed analysis of sectoral steam use (after implementing end-use efficiency measures) to estimate the impact of cogeneration, the ACEEE uses a simpler approach based on total steam use and assumed effectiveness of policies. Both studies also used different assumptions for the investment and installation costs of new cogeneration equipment. However, these differerences do not fully explain the differences in CHP results for both studies.

All studies have used the relative low energy prices as used in the AEO scenarios (25, 26). Generally, the AEO scenarios assume a drop in coal and electricity prices, and a small decrease in oil and gas prices. Price effects are modeled in the studies through the public benefit charge, as well as cap and trade systems (Tellus, and the CEF advanced scenario). The public benefit charge is low in all studies and is unlikely to affect energy-use patterns in itself. The impacts of public benefit programs financed by the charge are likely to be more profound and have received more attention as such in all studies. The cap and trade system results in a price effect in both studies. As only the CEF study has implemented cap and trade systems outside of the electricity sector, it is impossible to compare the effects of a cap and trade system on industrial energy use between the different studies. Hence, we assess the effects on total energy use in the United States. The emission reduction in the Tellus study (allocated to the power generation sector) is estimated at almost 10% of the total emission reductions in the Kyoto compliance scenario and almost 16% in the climate protection scenario (18) by 2010. In the the CEF advanced scenario (19), a cap and trade system (modeled as permit cost equivalent to $50/tC) is implemented after 2002 in a gradual way. By 2010, the cap and trade system results in 2% energy savings compared with the baseline scenario and a higher reduction (6%) in carbon emissions.

The different approaches to cost used in the studies point out the need for a consistent methodology. The CEF study takes 1 year of investment and one increment of energy savings and evaluates using a discount rate corresponding to a marginal return on energy efficiency investments; it also includes program costs. The Tellus and ACEEE studies use the investments and energy savings from the entire study period and a low financial discount rate, while excluding program costs. Each of these approaches leads to different interpretations of similar data.

Other recent studies have also assessed future energy use in US industry. However, we have not included them in this review because they either evaluate only selected energy policies (37) or do not explicitly address policies (4). The analysis of the Climate Change Technology Initiative prepared by the EIA (37) assesses for industry only the impact of a tax incentive for cogeneration until 2003 and is incomparable to other studies, which assessed longer time periods over which these measures are implemented (see above). The analysis of the effects on implementing the Kyoto emission reduction targets by the EIA does not address policies at all and only assesses energy and economic impacts of different emission reduction goals. In this sense, this study does not allow comparison of the results (e.g., reduction levels by sector, costs of emission reduction) of other policy studies. The Kyoto assessment of the EIA estimates very high costs to the US economy because of the lack of flexibility in achieving the targets set. A recent study (39) shows that increased flexibility (e.g., economic restructuring to less energy-intensive activities) in the reaction of the economy on the challenge put forward by climate change leads to reduced costs of climate change mitigation. Other studies (24, 40) have shown that increased flexibility in the form of alternative technologies may lead to different results in future energy use. Increased flexibility of models with respect to policy impact may also lead to further reductions in the estimates of GHG emission mitigation costs.

6. CONCLUSION AND RECOMMENDATIONS

We are beginning to evaluate and model the contribution policy interventions make toward improving energy efficiency. We reviewed three recent policy studies assessing the impact of energy efficiency policies in the United States. All studies model the policy impact rather than the policy itself. This is due to the complex interaction between policies and stakeholders. Often the policy impacts are based on assumptions, as the effects are not certain, e.g., the effect of R&D on technology development. Still, the studies represent an important step in the analysis of climate-change mitigation strategies. Most models only incorporate pricing tools, which recent studies have proven to be insufficient to estimate the impacts, costs, and benefits of mitigation strategies.

The reviewed studies are a first effort to capture the effects of nonprice policies. Although the methods used to estimate the effect vary from crude to highly detailed, the studies contribute to a better understanding of the role of policies in improving energy efficiency and mitigating climate change. Recent studies have shown that flexibility in technology choice and in economic rigidity contribute to a lower estimate of climate-change mitigation costs. These studies have shown that flexibility in policies used to improve energy efficiency and reduce greenhouse gas emissions may also result in lower costs for society and industry.

Studying policies for the industrial sector is no easy task because this sector is the most diverse and, arguably, the most challenging energy-demand sector to model. The challenges presented by modeling industrial-sector energy use are many but fall into two categories: appropriate level of detail (i.e., sector, technology, and policy) and representing decision making. In every case there are trade-offs to be made because of the availability of information, the policy/forecasting questions to be addressed, and the modeling methods that are implemented. When considering the trade-offs, it is important to keep a clear perspective on the question(s) the model is designed to answer and on the complexity of the system the model is representing.

A better understanding of decision-making behavior, technology choice, and policy impact and effectiveness is needed to improve our understanding of the potential effectiveness of future energy efficiency policies, as well as to improve policy modeling. Parametric models need not be limited to simple linear regression or “unexplained” exponential time-trends analysis. The development and accessibility to advanced statistical tools allows the analyst much more freedom. Statistical analyses of large data sets of company-specific (or even investment specific) information can help to capture greater realism about behavior or technology performance. Nonlinear estimations allow for more realism in specifying parametric relationships for conservation supply curves, technology adoption and diffusion, or technical change.

Policy evaluations can help to provide a better understanding of the impacts as well as effectiveness of policies. Including the lessons learned from policy evaluations is important for modeling of price and nonprice energy efficiency policies. For all policies, but especially for new flexible and innovative policies, evaluation should be an integral element of policy design. However, currently, in-depth evaluations of industrial energy efficiency policies are rare.

The use of harmonized costing methodologies will enable assessment and comparison of the results of different studies. Policy makers using the results of such models need to be able to understand the results in an unambiguous way.

With these developments, the current and next-generation policy models and studies have the potential to become richer representations of the industrial sector. However, industrial models will still differ in approach as they evolve according to the interests of their developers and the needs of policy makers. There is never likely to be a "one-size-fits-all" approach to industrial modeling. Instead the challenge will remain to have the "right tool for the right question," because if all you have is a hammer, everything starts to look like a nail.

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